Challenges of Machine Learning for eVTOL Reliability and Safety

Marcos Aurelio Salvador

Polytechnique Montréal, Canada
E-mail: marcos.salvador@polymtl.ca

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Abstract

The increasing number of requests for type certification received by the European Union Safety Agency on Vertical Takeoff and Landing (VTOL) aircraft attests to the expansion of frontiers in Urban Air Mobility (UAM). In addition, it has revealed the interest of traditional airplane and helicopter manufacturers in this new technology, all the while highlighting the emergence of new players developing their respective versions of electric-powered VTOLs (eVTOL). The perspective of eVTOLs going into service in the coming years for the transport of passengers raises new safety concerns. Indeed, it is necessary to ensure the reliability and safety aspects of those aircraft systems that will be flying under new operational missions, differing from current fixed wing (airplanes) and rotorcraft (helicopters) aircraft. At the same time, the evolution of aircraft systems monitoring technology is making it possible to acquire increasing amounts of data. The high complexity of new systems, combined with the huge amount of data provided, can make the decision-making process more difficult for pilots. Machine learning makes it possible to evaluate this data and improve reliability and safety.

Even as the number of aeronautical accidents has decreased over the last years, 60–80% of those accidents are the result of human failure. In the initial implementation and operation stages of eVTOLs, machine learning

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(ML) can support pilots by using aircraft data to predict system failures and contribute to improve reliability and safety. Then, at an advanced stage of eVTOL operation, ML may help reduce human interaction with the aircraft, paving the way toward fully autonomous aircraft. The association of ML with technologies such as Digital Twins and 6G networks has the potential to enable safe and reliable autonomous flight. However, the introduction of eVTOLs will also increase air traffic in highly populated areas and thus needs to be studied to support the incorporation of the future autonomous aircraft. This paper addresses the main challenges for the incorporation of ML in the upcoming eVTOL fleet and its potential contribution to aircraft systems reliability and safety. It also explores the need for the use of ML techniques in a more autonomous air traffic management systems the face of increased air traffic.

Keywords: Machine learning, vertical take-off and landing, digital twins, aircraft safety, aircraft reliability, complex systems, 6G networks, air traffic management.

1 Introduction

Improved safety and reliability in the aerospace industry has resulted in a decrease in the number of accidents. However, as systems evolve, they become more complex. To ensure that they work as planned, a monitoring system is constantly acquiring data about their status and parameters. The volume of data stored in databases has doubled every 20 months [1]. A similar increase can be expected in the amount of data generated by the fleet of aircraft operating around the globe.

As the development of the first generations of eVTOLs progresses, ensuring that their complex systems work in a safe and reliable manner is a prime requirement. Manufacturers, suppliers and certification authorities have been working to define the rules for certifying this kind of device, and ensure the safety of aircraft, flight crews and passengers. In support to assuring safety, machine learning techniques have the potential to help analyse the huge amount of data being generated by eVTOLs. Since machine learning techniques exceed the capacity of human beings to analyse large volumes of data, they may aid in discovering patterns that may lead to catastrophic system failures. When associated to technologies such as Digital Twins from Industry 4.0 and 6G communication networks, the real-time decision-making capability of machine learning can contribute to the improvement of eVTOL fleet safety and reliability.

This paper addresses the potential for the implementation of machine learning combined with digital twin and 6G network technologies to support future eVTOL fleet safety and reliability. It is divided in four sections. Section 1 gives an overview of the potential benefits of combining ML, 6G networks and digital twins. Section 2 provides an overview of those different technologies. Section 3 gives a literature review on those technologies and their potentials when combined to ensure safety and reliability , and Section 4 outlines possible areas for future research.

2 Background and Purpose of Study

The following background sections provide an overview of machine learning, in relation with artificial intelligence and data mining; eVTOLs; and the technologies that may be used to support aircraft systems safety and reliability, such as digital twins and 6G networks.

2.1 Artificial Intelligence, Data Mining and Machine Learning

Artificial intelligence

Artificial intelligence (AI) refers to the capacity of a system to interact with its environment and perform an action correctly [2]. To perform any kind of action, an agent must interact with its surroundings; based on the knowledge gathered through that interaction, the agent does the "right thing" or executes the most appropriate response considering the circumstances [2]. A system ruled by AI is able to interchange with its environment in order to achieve its goals. Even if the system's surroundings change, the embedded AI will keep achieving its goals: that is why such systems are called "intelligent agents" [3]. The self-driving system present in autonomous cars is an example of an intelligent agent.

Data Mining

The huge volume of data in databases is called Big Data. The information inside Big Data, which is stored in its datasets may have important knowledge hidden inside. The automatic extraction of this valuable information is known as Data Mining. Data Mining ultimately reveals hidden knowledge in the form of patterns [1].

Machine Learning

Machine learning (ML) provides the techniques that allow the extraction of valuable information from datasets. Machine learning can be defined as a computational method that uses the experience to improve its performance and provide accurate predictions [4].

It is important to highlight that ML is based on observing and learning, which is a passive action that allows a prediction, while AI is based on an intelligent agent which interacts with its environment to accomplish a goal, and it is an active action [5].

The ML learning techniques can be divided in two categories:

- Supervised: the data is labelled; inputs are known as if identified by a label. As an example, a system generates a signal that is read by a sensor. If it is previously known whether the signal represents a health operation of the system or a failure condition, this information is the label.
- Unsupervised: the data is not labelled; the patterns in the input data must be found.

2.2 Vertical Take-off and Landing Aircraft

Urban Air Mobility (UAM) has been defined as "a spectrum of new aviation capabilities serving densely populated areas with a variety of public and commercial services" [6]. The idea of an aircraft capable of vertical take-off and landing (VTOL) has been evolving for a long time. From the drawings of Leonardo da Vinci to the successful creation of the helicopter, a lot of progress has been made. Nowadays, helicopters are a common feature in the UAM of the major cities around the planet.

In recent years, the aerospace industry has witnessed the development of a new category of aircraft, which represent an evolution of the VTOLs and thus signal the next chapter in urban air mobility. According to Littell, electric vertical take-off and landing (eVTOL) aircraft are now in the spotlight of the aerospace industry because they have the potential to "change the urban transportation paradigm from traditional ground-based vehicles (cars, taxis, buses) to air-based eVTOL vehicles which can be summoned" [7].

The initial target for eVTOLs is the transport of passengers. With the United Nations forecasting that 68% of the world population will live in cities by 2050 [8], there is a perspective for an increasing need for new ways of transport. There is also a promising future market for human mobility in urban areas. However, this new kind of aircraft brings new challenges in terms of reliability and safety. One of the key areas of concern is the fact that eVTOLS would represent a new kind of aircraft mission. With shorter flights and high frequency take-offs and landings, eVTOLs represent an unusual scenario in the aerospace industry. Accordingly, their specific requirements must be addressed by the manufacturers, suppliers, and certification authorities to ensure safety.

2.3 Industry 4.0 (i4.0) and Digital Twin

The term Industry 4.0 (i4.0) was first used at the Hanover Fair in 2011 [9]. It refers to the fourth industrial revolution, generally associated with the introduction of internet technology [9]. It follows the first industrial revolution, associated with the creation of mechanical looms driven by steam engines (around 1780s). The second corresponds to the creation of the continuous production lines, such as the one applied to the Ford Model T. The third industrial revolution came with the creation of the programmable logic controller (PLC), and it is still in place. Of course, the events that mark the starting point of each revolution age are controversial and may differ from one source to another.

The technologies of Industry 4.0 can be classified in 10 groups. The most relevant for this study are:

- Big Data: covered in chapter 2.1.
- Artificial Intelligence: covered in chapter 2.1.
- Simulation systems: These allow for the imitation of a set of circumstances that a system may be submitted to during its regular operation. One of the fields of simulation systems is known as "digital twins". A digital twin is a virtual model of a physical object, capable of exchanging information with its physical version . As an example, a sensor can capture the signals corresponding to the status of parameters measured in a machine; those signals can then be transferred to a digital model of the machine, such that both the machine and virtual model can receive and transmit data in real-time and interfere in one another's states.

Assuming the physical object is a manned/unmanned piloted aircraft or automobile, the digital twin can contribute with the exchange of data, processing information to identify patterns and act in case of a system degradation that could lead to a malfunction or catastrophic failure. Consequently, a digital twin can contribute to a vehicle's overall safety and reliability.

2.4 Aircraft Reliability and Safety

The number of aeronautical accidents has decreased over the last years, in large part thanks to technological advancements in the aerospace industry. However, as aircraft systems become more and more complex, and demand more difficult analysis, those analysis represent a new set of challenges to ensure the safety and reliability of those systems.

Complex safety-critical systems have been defined as "system[s] whose safety cannot be shown solely by test, whose logic is difficult to comprehend without the aid of analytical tools, and that might directly or indirectly contribute to put human lives at risk, damage the environment, or cause big economical losses" [10].

Ensuring that a system is safe involves ensuring that it is free of single failures that may lead to catastrophic outcomes. Therefore, a systems must be reliable in order to allow to keep its level of safety. Reliability refers to "the characteristic of a given system of being able to operate correctly over a given period of time" [11].

The prime benchmark for certifying safety in aeronautics is called "airworthiness." Airworthiness corresponds to the level of safety for an aircraft to be considered acceptable for in-service activities, i.e., apt to operate in the commercial transport of passengers. Airworthiness standards are defined in certification specifications (CS). This paper uses the CS from the framework of the United States Federal Aviation Administration (FAA) and the European Unit Aviation Safety Agency (EASA). They are also valid for other certification authorities [12].

The certification specification and acceptance means of compliance for large aeroplanes (CS25) recommends the techniques to be adopted and the objectives that may be followed in order to show that a system has a fail-safe design. Its goal is to ensure that aircraft systems will not suffer a catastrophic outcome as result of a single failure. The CS 25.1309 contains the certification regulations for the systems onboard an airplane. These regulations are supported by practices such as the AC 25.1309, which defines quantitively and qualitatively the level of severity and probability of failure conditions. Failure conditions are the scenarios resulting from a failure, i.e., loss of deceleration capability on ground.

The probability of occurrence of a failure is 1. That means that failures will happen, but they can be predicted with a reliable level of confidence. In the case of eVTOLs, it will be important to have real-time access to the aircraft data in order to mitigate risk of a failure before it occurs. To support fast detection and intervention in case of possible issues, a reliable and high-speed network is necessary. The 6G network is a promising alternative to permit the transference of data at ultra-high speeds.

2.5 6G Network Technology

In the field of telecommunications, "6G" refers to the sixth generation of wireless communication networks. It was preceded by the 1G (first generation), when cellular systems were based on analog standards from the 1980s. The 2G (second generation) was launched in the early 1990s and was based on digital networks. In the late 1990s, the 3G (third generation) was introduced, with a higher transfer rate starting at around 144 Kbit/s (kilobytes per second). The 4G (fourth generation) came around the 2010s, bringing features such as gaming services and IP telephony. The current technology network, 5G, was launched around 2020 and is currently in expansion. Its main benefits include high speed (1Gbit/s) and low error rates.

The integration of machine learning techniques in 6G networks will enable the adoption of the "Predict-to-Prevent" approach. By anticipating possible threats within the 6G network [13], ML helps make the whole system more reliable. The interoperability between ML, 6G, and technologies from the i4.0, such as digital twins, has the potential to contribute directly to the improvement of the reliability and safety of future eVTOL fleets.

3 Literature Review

The recent increase in the cadence of development of eVTOLs has generated excitement among manufacturers, designers, and researchers. However, there are multiple uncertainties on how the industry will mature [7], there is a question on how the eVTOLS will integrate with technologies that are under development, such as 6G, or technologies that are not mature, such as digital twin.

Yang and Wei [13] have identified the need for a shift from human-centred air traffic management systems to more autonomous models, to make Urban Air Mobility operations as safe as possible. Their work contributes to the assessment of the potential traffic generated by eVTOLs and provides a computational algorithm for preventing possible collisions. However, it does not address the need for monitoring the traffic of the future delivery drones that may share space with eVTOLs.

Liao et al. [14] tested a real-world vehicle-to-cloud (V2C) Digital Twin in the automotive industry. Specifically, they tested its capacity to successfully use a highway ramp to access a merging roads system. Their work opens the door for further questions such as the required frequency of updates of Digital Twins on the cloud service.

Bauranov and Rakas [15] apply the Bayesian Belief Network to explore the risks of eVTOL system failure and pilot workload impacting the safety of flight. Their work shows that risks like bird strike will increase with the implementation of eVTOLs. Also, their assumptions rely on the development of a new air traffic control system.

Saboor et al. [16] present a view of the future of wireless communication in the Urban Air Mobility field. They argue that Unmanned Aerial Vehicles (UAVs), such as drones, can be used to improve the 6G technology Intelligent Transportation System (ITS).

Zaid et al. [17] outline the superiority of NTFP (Network Tethered Flying Platforms) when compared to the current technology of ground base stations. Their work contributes to discussions on the development of autonomous vehicles and the safety of eVTOLs, with infrastructure based on NTFPs.

Belmekki and Alouini [18] discuss the use of NTFPs, Low-Altitude Platforms (LAPs) and High-Altitude Platforms (HAPs) to enable the use of 6G technology with maritime, flying cars (horizontal take-off and landing vehicles), and terrestrial vehicle communications. This work contributes to the geometrical, economical and performance analysis for wireless communication platforms.

Littell [7] presents the required level of safety for eVTOLs. It discusses the regulatory approach and potential guidelines. It contributes to ongoing efforts to improve the level of safety for eVTOLs.

The combined implementation of 6G network, Digital Twin technology and Machine Learning to ensure eVTOL systems and air traffic control safety and reliability remains an unexplored area.

4 Machine Learning in Support of eVTOL Reliability and Safety

This study aims to evaluate the potential challenges for the use of machine learning to support the safety and reliability of the future fleet of eVTOLs. It also considers its potential applications for eVTOL air traffic management. Below, two scenarios are developed. The contribution of ML and constraints are presented. The first scenario assesses how the logical analysis of data combined with 6G networks and digital twins could contribute to improving aircraft reliability and safety. The second scenario foresees the implementation of ML to support aircraft traffic control.

Scenario #01 – ML and digital twins to support aircraft reliability and safety through a 6G network

In the coming years, it is expected that a fleet of eVTOLs will go into service. In their first generation those aircraft will be manned, but future generations are expected to be fully autonomous. It is imperative that safety and reliability must be ensured for all those successive generations.

Salvador et al. [12] state that aircraft safety is not self-sustaining: the aircraft is delivered with an acceptable level of safety and this level must be maintained. Machine learning techniques for pattern recognition combined with digital twins and supported by real-time data transfer on the 6G network can improve aircraft reliability and safety, making it possible to avoid potential failures before they occur.

As an example, eVTOLs will have complex systems such as flight by wire (FBW), which converts the mechanical commands from the flight crew into signals to move the aircraft actuators surfaces, providing manoeuvrability of the aircraft during flight. The FBW is the primary means of controlling the aircraft in-flight. Therefore, a failure of the flight controls can be catastrophic.

The system control unit provides monitoring and command of the actuators. The data provided by sensors (monitoring) to the system may pertain to: the actuators' position, the hydraulic fluid level, the hydraulic fluid temperature, or alternating current (AC) or direct current (DC) signal input, among others. In the event of a failure, the failed component(s) will be reported to pilot(s) and on-ground maintenance personnel.

The ultra-high speed of the 6G network provides an infra-structure capable of supporting the connectivity of a fleet of eVTOLs. The network will allow real-time data transmission between the aircraft and a digital model monitoring the status of all embedded systems through a digital twin approach. The digital model uses machine learning techniques that will identify patterns among the monitored signals to predict possible failures, increasing the safety of the aircraft and allowing the maintenance crew to predict components' remaining useful life (RUL). Thus, when used in conjunction, 6G and digital twins may help improve the reliability of eVTOLs systems.

However, as a digital twin is a virtual model of an eVTOL, multiple digital models will be operating simultaneously. The information learnt from one aircraft by machine learning needs to be shared to other digital models. The coordination of this real-time traffic of information may represent a challenge in a scenario where autonomous aircraft need to be constantly monitored and large volumes of data are acquired.

Scenario #02 – ML, 6G network and artificial intelligence to ensure safety in air traffic control management of urban areas

As previously discussed,, the introduction of eVTOLs in the urban air mobility will represent a completely new type of aircraft mission. The high concentration of these devices over very populated areas will require an air traffic control management system capable of dealing with a dense air traffic flow.

Zaid et al. [17] discuss the Network Tethered Flying Platforms (NTFPs) as an option to enable 6G communication networks for eVTOLs and unmanned aerial vehicles (UAVs), such as drones. Those flying platforms are connected to the ground by a tether, which restricts their movement. The infrastructure may use balloons or other kinds of stationary flying devices at altitudes that may vary from 150 m to 5 km. When positioned at lower altitudes, the system presents low latency (delay in the data transmission), while higher altitudes bring wider coverage.

The implementation of autonomous eVTOLs requires highly coordinated management of the traffic, where eVTOLs, delivery drones and NTFPs need to be harmonized to avoid the risk of collision between them or the risk of collision to the tether connecting the NTFPs to the ground. Embedded aircraft collision avoidance systems may be required on those three kinds of devices to avoid accidents. However, beyond the 6G communication between those aircraft, the air traffic control system also must use the ultra-high-speed communication capabilities provided by the network. Artificial intelligence shall be embedded in the monitoring system, so that in case of emergency one or more aircraft can perform coordinated extremely manoeuvres to ensure the safety of passengers and on-ground personnel. The more populated a city is, the more challenging the air traffic management will be in this area.

The incorporation of artificial intelligence and machine learning in the traffic control systems will make it possible to acquire knowledge from training scenarios in different emergency situations. In the event of an emergency, AI will allow for the re-configuration of traffic at an ultra-high speed in the 6G network. It will also enable the identification of patterns that could lead to threats, which will contribute directly to the safety and reliability of eVTOLs and their crew.

5 Conclusion

Machine learning and pattern recognition have the potential to facilitate the deployment of eVTOLs in urban air mobility. They namely can improve the safety and reliability of the fleet's embedded system as well as traffic control. The association of machine learning with digital twin and 6G network technologies can aid in the prediction of failures and the evaluation of remaining useful life of components in real-time. The identification of patterns will play a fundamental role in these advances. However, the interoperability between virtual models and ML, and the availability of coverage by the 6G network are challenges that need to be solved by manufacturers, suppliers, researchers and certification authorities.

In the air traffic management field, the numerous amounts of aircraft sharing the space in high-density populated areas is a concern from the viewpoint of collision avoidance. The deployment of EVTOLs, delivery drones and the infrastructure for NTFPs will require machine learning and artificial intelligence to overcome the challenges of a congested sky.

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Biography

Marcos Aurelio Salvador is an engineer with more than 13 years of experience in the aerospace industry. He is currently pursuing his M.Sc. in the department of Industrial Engineering and Applied Mathematics, at École Polytechnique de Montréal (Canada). He holds a B.Sc. in Electronic Engineering from the Faculty of Engineering São Paulo, Brazil (2005). His work in the field of Reliability, Availability, Maintainability and Safety (RAMS) has focused on critical systems safety analysis and risk analysis and management. His research interests are Condition-Based Maintenance, Machine Learning and Pattern Recognition, Data Analytics, Industry 4.0, and Autonomous and Interoperable Flight.